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Carbon fluxes and budgets of intensive crop rotations in two regional climates of southwest Germany

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ABSTRACT

The carbon (C) sequestration potential of croplands has recently become a subject of debate because it may contribute significantly to global climate change mitigation. By contrast, carbon dioxide (CO_2) emissions from German croplands have continuously increased over the past decades as a result of soil organic carbon (SOC) losses. Contrasting results, however, have been obtained on the C sink or source function of European croplands based on long-term experiments and rather recent eddy covariance (EC) measurements. Over a period of eight years (2010–2017), we measured the net ecosystem exchange (NEE) of CO_2 on six intensively managed cropland sites in two climatically different regions of southwest Germany (Kraichgau (KR) and Swabian Jura (SJ)) using the EC technique. Additionally, we measured aboveground crop biomass at three development stages and estimated management-related C inputs and exports. The inter-annual on-site variability of cumulated annual NEE was large, and neither the region nor the different sites significantly affected NEE budgets. Winter rapeseed showed the lowest CO_2 uptake capacity among the observed crops, and the mean annual NEE in the years with winter rapeseed harvest was significantly lower compared to winter wheat, silage maize and winter barley. On average over 46 site-years, annual NEE showed a distinct CO_2 uptake of -2580 kg CO_2-C ha^{-1} yr^{-1}. Considering management-related C fluxes, the resulting net biome productivity (NBP) indicated a C source function of the study sites with mean annual losses of 1190 kg C ha^{-1} yr^{-1}. Due to high C removals after whole plant harvests, silage maize cropping resulted in significantly higher C losses of 4280 kg C ha^{-1} yr^{-1} compared to winter rapeseed, winter wheat and winter barley, with mean annual NBPs of 1430, -188 and -1340 kg C ha^{-1} yr^{-1}, respectively. Consequently, a higher share of exported C in annual NBP resulted in higher C losses. We conclude that the recently increased importance of silage maize in crop rotations destabilizes SOC stocks, threatening the efforts in enhancing soil C sequestration. This calls for further investigations on the C sequestration potentials of more diverse crop rotations including perennial phases.

1. Introduction

The land area covered by croplands plays a substantial role for the global carbon (C) cycle due to its large extent and highly dynamic nature with frequent disturbances of the soil-plant system. In Germany, 33% of the land area was covered by croplands in 2016, corresponding to 71% of the total agriculturally utilized area (Destatis, 2017). Estimated CO_2 emissions from German croplands reported under the

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United Nations Framework Convention on Climate Change (UNFCCC) amounted to 14577 Gg in 2016, equivalent to 1.9% of total German CO_2 emissions. These cropland CO_2 emissions have been steadily increasing, i.e. by 17.2% since 1990 (UBA, 2018), underlining the potential of croplands for greenhouse gas (GHG) mitigation (Smith et al., 2008). A large proportion of the reported cropland CO_2 emissions is attributed to organic soils, whereas the rest is assigned to grasslands recently converted to croplands. Croplands under good agricultural practice are generally considered to show stable soil organic carbon (SOC) contents over the long-term (Körschens et al., 2014). In contrast, recent measurements from eddy covariance (EC) flux tower networks demonstrated that croplands act as C sources to the atmosphere when all relevant C fluxes of the agroecosystem are considered (Ceschia et al., 2010; Prescher et al., 2010).

Measures proposed to mitigate C losses from croplands typically involve management practices such as cover crops (Poeplau and Don, 2015), nutrient supply, tillage (Eugster et al., 2010) or residue management (Lal, 2004). Moreover, a change in land use intensity is potentially promising to enhance C sequestration or reduce the depletion of SOC stocks under certain conditions. In low-productivity systems, agronomic measures that increase plant biomass can build up SOC stocks by allocating more C into the soil via roots and harvest residues (Smith et al., 2005). Under conditions unfavorable for intensive cropping, however, reducing land use intensity or even abandoning these areas (i.e. land use change) can be the most effective measure for reducing SOC losses (Smith et al., 1997).

Robust information on ecosystem functions with regard to C budgets and thus climatic impact can be gained only from long-term measurements. This is because the inter-annual variability of C exchange is large (Moors et al., 2010). Studying the full C budget of a cropland and assessing the net biome productivity (NBP) requires considering all relevant C fluxes in the system. Alternatively, the temporal development of SOC stocks has to be monitored over many years to decades with a consistent methodology (Smith et al., 2010). These types of observations are rare, although some valuable networks of long-term experiments exist (Smith et al., 2002). Robust agroecosystem models are essential to extrapolate C budgets of croplands to larger spatial scales (Klosterhalfen et al., 2017), underlining the importance of the aforementioned long-term experiments and observations. Moreover, accounting for spatial heterogeneity is essential for upscaling C fluxes in agricultural landscapes (Premke et al., 2016).

Several multi-year observations that used the EC method to study the net ecosystem exchange (NEE) of CO_2 over croplands are available (e.g., Kutsch et al., 2010). For typical crops grown on mineral soils in intensive crop rotations, the seasonal and annual NEE often shows a net CO_2 uptake. Accordingly, the gross primary production (GPP) from photosynthesis is higher than the respiration of the total ecosystem (R_{ECO}). Nonetheless, most of the fixed C is removed from these systems via harvest, often resulting in net C losses to the atmosphere (Ceschia et al., 2010; Loubet et al., 2011; Schmidt et al., 2012).

A well-known limitation of the EC method is the imbalance between measured turbulent energy fluxes and the available energy at the land surface (Foken, 2008). One potential reason for the energy balance gap is uncaptured low-frequency fluxes, also termed mesoscalic eddies, which can be analyzed by varying the averaging time for flux computation (Mauder and Foken, 2006). However, investigating the extent to which the energy gap also affects CO_2 fluxes and thus C budgets is challenging (Kidston et al., 2010). Applying the ogive or cumulative flux analysis enables determination of a suitable averaging time (Foken and Wichura, 1996). Recently, an ogive optimization method was developed following the idea that low-frequency influences must be separated from vertical turbulent fluxes in order to isolate the local exchange processes of interest (Sievers et al., 2015). Using this new approach, Sievers et al. (2015) demonstrated that the relative differences between fluxes estimated by a common 30 min averaging interval and the ogive optimization can be very high (up to 98%) when fluxes are rather low. Importantly, the method was applied to field sites without agricultural management: it remains uncertain how much low-frequency contributions might affect the CO_2 exchange of intensively managed croplands.

Typically, studies based on EC measurements are performed as single-field observations in a given region or environment (Osborne et al., 2010). This yields insights into temporal variability but leaves the spatial variability between different fields with the same management and site properties unexplored. Here, we present results from EC measurements of CO_2 exchange over eight years in two regions of southwest Germany with different pedoclimatic conditions. In each region, three EC stations measured the CO_2 fluxes over separate adjacent or nearby arable fields. The main objective of this study was to investigate whether systematic differences exist between the annual C budgets of sites in different pedoclimatic regions, between different sites within the regions and between the most frequently grown crops in intensively managed crop rotations. We hypothesize that the study sites represent C sources due to recent intensification and specialization processes of the respective arable production systems. The corresponding C losses are expected to be higher at sites with larger SOC stocks.

2. Material and methods

2.1. Study sites

The measurements were performed on a total of six sites in two different regions of the federal state Baden–Württemberg in southwest Germany. The two regions, Kraichgau (KR) and Swabian Jura (SJ), differ in their pedoclimatic conditions as a consequence of parent material and elevation. For detailed information on the two regions, see Wizemann et al. (2015).

In the KR region, the study sites were located close to the city of Pforzheim at 48.9°N, 8.7°E and 319 m above sea level (a.s.l.) (Fig. 1). Over the period 1981–2010, the mean annual temperature was 9.4 °C and the mean annual precipitation was 889 mm at the nearby weather station Pforzheim-Ispringen (48.9°N, 8.7°E, 333 m a.s.l.; German Weather Service, 2016). The soils for this study developed from deep Holocene silty loess layers (Table 1). They are typical for the KR region and have been classified as Stagnic Luvisols (WRB, 2015) due to periodically occurring stagnic water conditions, particularly in winter and spring. The underlying rock material is shell limestone (Ingwersen et al., 2011). According to the three installed EC stations, the sites were named EC1, EC2 and EC3, located on three adjacent arable fields aligned in west-east direction (Wizemann et al., 2015; Imukova et al., 2015). The fields are managed by a local farmer with regular applications of mainly mineral fertilizers and pesticides typical for conventional cropping systems on high yielding sites in Central Europe. During the 2010–2017 observation period, only three main crops were harvested on the three sites. Nitrogen fertilization (N) intensities were rather high, particularly in those years when organic fertilizers were applied additionally. No organic fertilizers were applied on EC3. The most frequent tillage procedure was moldboard ploughing (n = 17) followed by grubbing (n = 11) and disc harrowing (n = 6) (Table 2). The ploughing depth usually did not exceed 0.25 m.

The study sites in the SJ region were located at 48.5°N, 9.8°E and 690 m a.s.l. near the village Nellingen (Fig. 1). In this region, the climate is colder and wetter compared to KR, with a mean annual temperature and precipitation of 7.5 °C and 1042 mm, respectively, measured at the nearby weather station Merklingen during 1981–2010 at 48.5°N, 9.8°E and 685 m a.s.l. (German Weather Service, 2016). Of the three sites – named EC4, EC5 and EC6 – EC4 and EC5 were adjacent to each other, while EC6 was located about 1.5 km north (see Wizemann et al., 2015). Soils in SJ developed from Jurassic limestone and are typically shallow and much more heterogeneous with higher C stocks compared to KR (Table 1). Thus, the soil types differed between the

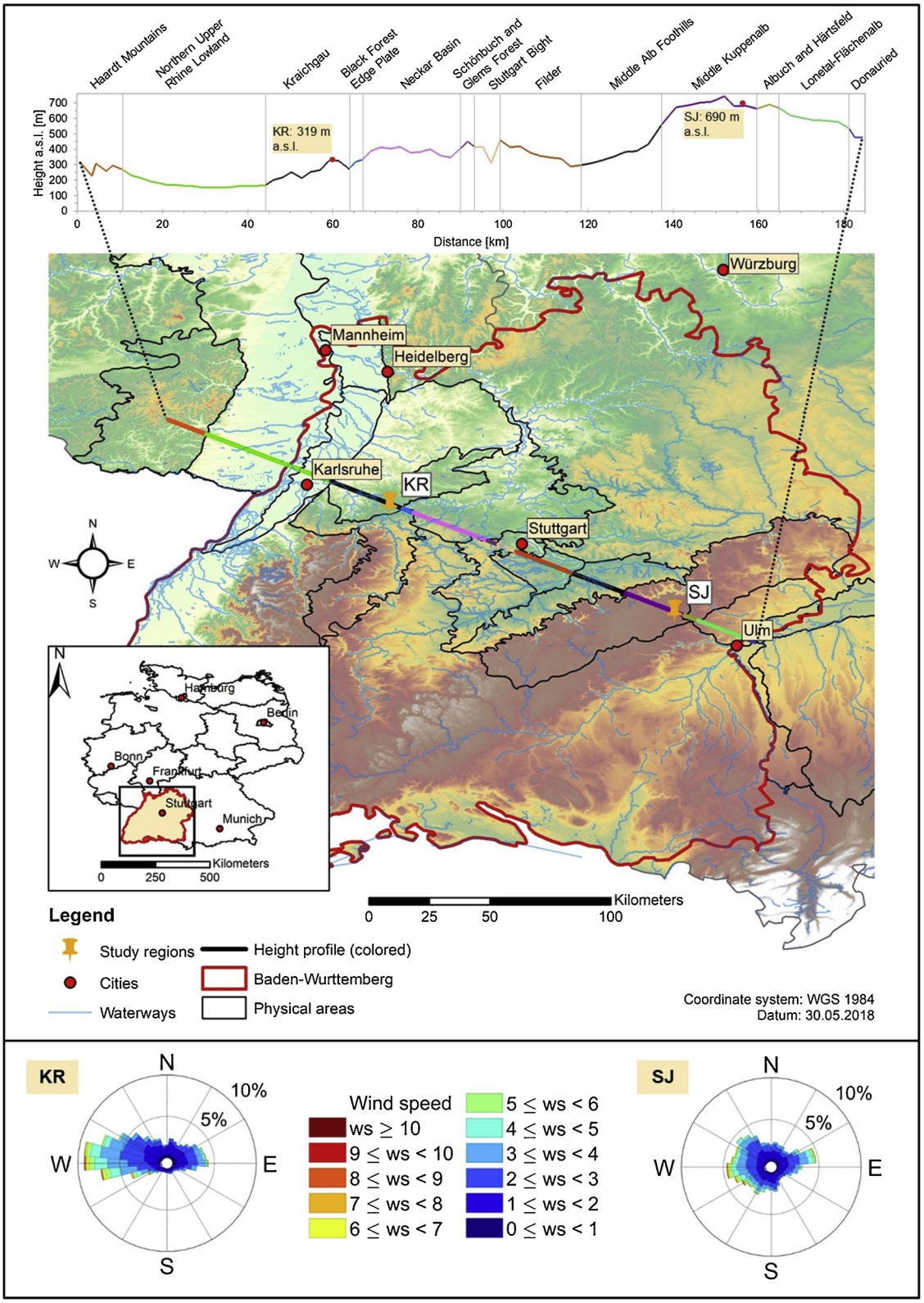

Fig. 1. Overview.
Top: Height transect through the two study regions Kraichgau (KR) and Swabian Jura (SJ). Middle: Geographical overview of the two study regions. Bottom: Rose diagrams of wind direction and wind speed. Wind data: average over eight years (2010–2017). Calculations based on data of eddy covariance stations EC1 and EC4 for KR and SJ, respectively.

Table 1
Top soil (0–30 cm) properties of the six study sites. EC1–3: Kraichgau, EC4–6: Swabian Jura. Ranges are standard deviations.

Site	Texture S/U/C[a] (% by mass)	Porosity (% by vol.)	Bulk density[b] ($g\,cm^{-3}$)	C/N ratio[b] (1)	C stock[b] ($Mg\,ha^{-1}$)	C concentration/annual change[c] ($g\,kg^{-1}/g\,(kg\,yr)^{-1}$)	Carbonate (% by mass)	pH (0.01 M $CaCl_2$)
EC1	2.5/79.4/18.2	48.3	1.29 ± 0.12	9.1 ± 0.5	32.0 ± 4.2	9.3 ± 0.8/−0.04[n.s.]	1.50	6.9
EC2	2.6/79.5/17.9	49.8	1.24 ± 0.14	10.7 ± 1.6	32.6 ± 8.4	10.0 ± 2.3/−0.20[n.s.]	1.38	6.2
EC3	1.8/81.1/17.1	48.3	1.25 ± 0.14	9.0 ± 0.4	27.6 ± 2.8	9.5 ± 1.1/−0.18[n.s.]	1.46	6.4
EC4	7.6/54.2/38.2	50.0	1.30 ± 0.19	9.5 ± 0.3	67.8 ± 11.6	21.9 ± 5.7/0.39[n.s.]	2.62	6.9
EC5	2.8/68.3/28.9	48.3	1.22 ± 0.12	9.7 ± 0.7	71.8 ± 7.6	20.1 ± 2.7/−0.04[n.s.]	2.95	6.4
EC6	3.6/49.8/46.6	56.0	1.24 ± 0.14	9.9 ± 0.2	80.9 ± 9.9	22.8 ± 5.7/0.92[*]	4.72	7.0

[a] Fractions of sand (S), silt (U) and clay (C).
[b] Samplings from 8 and 9 November 2017.
[c] Mean values of regular samplings between May 2009 and November 2017 as well as the mean annual change in carbon concentrations calculated by linear regression of the time series with $n = 8$ (EC3), $n = 9$ (EC1, EC2, EC4), and $n = 10$ (EC5, EC6). n.s. = not significant, [*]Significant with $0.01 < p < 0.05$.

three sites and were classified as Calcic Luvisol (EC4, solum thickness 0.45 m), Anthrosol (EC5, solum thickness > 0.9 m) and Rendzic Leptosol (EC6, solum thickness 0.2 m) according to WRB (2015). As in KR, field management can be classified as conventional and intensive cropping. On average, the N fertilization intensity was lower on EC4 and no organic fertilizers were applied except for the last season. As the farmer of field EC5 kept livestock, slurry was applied regularly. On EC6, organic fertilizers were applied mainly as biogas digestate with the highest fractions on total N input over all sites. Ploughing was carried out only in two years at EC5, whereas tillage was mainly restricted to harrowing at the shallower sites EC4 and EC6. Furthermore, the number of crop types grown was higher at the SJ than at the KR sites (Table 2).

2.2. Eddy covariance measurements

2.2.1. Instrumentation

In 2009, the six EC stations were set up in the center of the fields, ensuring 130 m (EC4) to 300 m (EC2) fetch in the main wind direction (W, see Fig. 1). All stations were equipped with an LI-7500 open path CO_2/H_2O infrared gas analyzer (LI-COR Biosciences, Lincoln, NE, USA) and a CSAT3 3D-sonic anemometer (Campbell Scientific Inc., Logan, UT, USA), installed 2–3 m above the crop canopy and oriented in southern (KR) and south-western (SJ) direction. Data were collected with 10 Hz and stored on a CR3000 data logger (Campbell Scientific Inc., Logan, UT, USA). Global radiation (R_g) and net radiation were measured with a 4-component net radiometer (NR01, Hukseflux Thermal Sensors B.V., Delft, The Netherlands) that were installed about 1.5 m above the canopy. The soil heat flux at 8 cm soil depth was measured with three replicates of heat flux plates (HFP01, Hukseflux Thermal Sensors B.V., Delft, The Netherlands) at each EC station. The CR3000 data loggers were used to store the 30 min averages of radiation, soil heat flux, air temperature (T_a) and humidity in 2 m height (HMP45, Vaisala Inc., Helsinki, Finland; EC2 from September 2016 and EC1 from December 2016: HC2S3 Hygroclip2, Rotronic GmbH, Ettlingen, Germany) and precipitation (ARG100, EML, North Shields, UK). Additionally, CR1000 data loggers (Campbell Scientific Inc., Logan, UT, USA) stored the 30 min averages of soil temperature (107, Campbell Scientific Inc., Logan, UT, USA), volumetric soil water content (CS616, Campbell Scientific Inc., Logan, UT, USA) and soil matric potential (253, Campbell Scientific Inc., Logan, UT, USA). For each of these three soil variables, five sensors were installed in different depths depending on the variable and the solum thickness at the SJ sites. For more details, including measurement accuracies, refer to Wizemann et al. (2015).

On five sites, the described instrumentation was operational during the observation period January 2010–October 2017. On 11 April 2017, however, the system on EC1 was changed. A new EC station equipped with an LI-7200RS enclosed path CO_2/H_2O gas analyzer (LI-COR Biosciences, Lincoln, NE, USA) and a HS-50 3D-sonic anemometer (Gill Instruments Ltd., Hampshire, UK) was installed. Long- and shortwave radiation was measured with a 4-component CNR4 net radiometer (Kipp & Zonen B.V., Delft, The Netherlands). Three self-calibrating heat flux plates (HFP01SC, Campbell Scientific Inc., Logan, UT, USA) were buried 8 cm below the soil surface. To measure soil volumetric water content as well as soil temperature, three HydraProbe II sensors (Stevens Water Monitoring Systems Inc., Portland, OR, USA) were installed at 5, 10 and 15 cm soil depth, respectively. Air temperature and humidity were measured by a HMP155 probe (Vaisala Inc., Helsinki, Finland) at this station. The soil and weather data were stored on an XLite 9210 data logger (Sutron Corporation, Sterling, VA, USA).

Power supply for all EC stations was ensured by two solar-power batteries with capacities of 12 V and 250 Ah each (Keckeisen Akkumulatoren e.K., Memmingen, Germany). The batteries were charged by four 20 W solar panels (SP20, Campbell Scientific Inc., Logan, UT, USA) at each station. During periods with low solar altitude, however, the power supply was generally insufficient to ensure the operation of the LI-7500. For this reason, no CO_2 fluxes were measured during winter time, mainly from late November until March. To assess the CO_2 exchange during winter time, direct methanol fuel cell systems with 45 W maximum power supply (Efoy Pro 800 Duo, FSC Energy AG, Brunnthal-Nord, Germany) were installed at EC2 and EC6 in autumn 2015. This enabled operating the CO_2/H_2O analyzers during the subsequent two winters at these sites.

2.2.2. Data processing and flux filtering

Turbulent fluxes were computed for 30-min intervals using the software package TK3.1 (Mauder et al., 2013). This program enabled spike detection (Vickers and Mahrt, 1997), planar fit coordinate rotation (Wilczak et al., 2001), correction of spectral loss (Moore, 1986), conversion of sonic temperature into actual temperature (Schotanus et al., 1983) as well as correction for density fluctuations and vertical mass transport (Webb et al., 1980). For quality classification of the calculated fluxes, the nine class flagging scheme after Foken et al. (2004) was used. To estimate the uncertainty of computed fluxes, the random error and the instrumental noise calculated by TK3.1 were summed up.

The processed 30-min fluxes were filtered by applying quality criteria that were chosen in order to remove unreliable data from the dataset on the one hand, but to provide sufficient data coverage for C budgeting on the other. The approach of Demyan et al. (2016), who used data from the same dataset for their respiration model, was modified accordingly. Here, we used data flagged with 1-6 as recommended for long-term observation programs. For additional despiking of half-hourly fluxes, we applied a median filter using the median of absolute fluxes of the previous four days; fluxes that were greater than 5-times this median were discarded from the dataset.

Table 2
Crop rotation, management and yields at the six study sitesduring the period 2010–2017.

Site	Period	Crop[a]	N fertilization		Tillage[c]	Yield[d]
			Total (kg ha $^{-1}$)	Organic (percentage)[b]		(Mg ha $^{-1}$ ± SD)
EC1 (14.9 ha)	2010	SM	273	27 (BD)	P	19.8 ± 2.4
	2010/2011	WW	170	/	P	10.2 ± 0.5
	2011/2012	WR	210	/	G	4.8 ± 0.4
	2012/2013	WW	179	/	DH, G	8.9 ± 0.9
	2013/2014	CC–SM	283	35 (CS)	G, P	23.2 ± 1.7
	2014/2015	WW	246	26 (CS)	P	9.4 ± 1.6
	2015/2016	CC–GM	213	/	DH, P	14.0 ± 1.6
	2016/2017	WW	183	/	P	8.2 ± 0.8
EC2 (23.6 ha)	2009/2010	WR	333	29 (BD)	G	4.4 ± 0.2
	2010/2011	WW	170	/	DH	9.4 ± 0.2
	2011/2012	CC–SM	272	27 (BD)	G, P	24.5 ± 1.4
	2012/2013	WW	180	/	P	7.9 ± 0.4
	2013/2014	CC–SM	210	/	DH, G, P	23.2 ± 1.2
	2014/2015	WW	246	26 (CS)	P	10.1 ± 0.9
	2015/2016	WR	173	/	DH, G	4.4 ± 1.0
	2016/2017	WW	183	/	P	9.5 ± 1.5
EC3 (15.8 ha)	2009/2010	WW	220	/	P	7.9 ± 0.9
	2010/2011	CC–SM	223	/	P, P	25.5 ± 1.8
	2011/2012	WW	203	/	P	9.9 ± 0.8
	2012/2013	WR	235	/	DH, G	7.2 ± 0.6
	2013/2014	WW	198	/	G	10.5 ± 1.1
	2014/2015	CC–SM	203	/	G, P	21.9 ± 2.1
	2015/2016	WW	202	/	G	6.9 ± 0.9
	2016/2017	WW	183	/	P	6.2 ± 1.3
EC4 (8.7 ha)	2009/2010	WR	205	/	DH, DH	2.8 ± 0.5
	2010/2011	WW	237	/	DH, DH	8.3 ± 1.9
	2011/2012	CC–SB	95	/	DH, G	8.9 ± 0.4
	2012/2013	WR	133	/	DH	1.8 ± 1.1
	2013/2014	WW	190	/	DH	10.4 ± 0.4
	2014/2015	WW	203	/	DH	9.9 ± 1.0
	2015/2016	CC–SB	80	/	DH	6.2 ± 0.7
	2016/2017	CC–SM	133	79 (CS)	DH	30.5 ± 11.8
EC5 (16.7 ha)	2009/2010	WW	245	14 (BD)	G, G	9.0 ± 1.2
	2010/2011	CC–SM	206	17 (CS)	G, DH	18.7 ± 1.6
	2012	SM	268	39 (CS)	DH	14.5 ± 1.7
	2012/2013	WB	227	25 (CS)	G	8.7 ± 0.3
	2013/2014	SP	170	35 (CS)	P, DH	6.6 ± 1.1
	2014/2015	CC–SM	192	16 (CS)	P, DH	17.3 ± 2.6
	2015/2016	CC–SM	151	/	DH, DH	21.8 ± 1.5
	2016/2017	WB	192	40 (CS)	DH	10.4 ± 2.1
EC6 (13.4 ha)	2009/2010	CC–SM	210	57 (BD)	DH, DH	14.8 ± 3.1
	2010/2011	WW	221	/	DH	9.5 ± 0.9
	2011/2012	WB	273	59 (BD)	DH	8.6 ± 1.3
	2012/2013	CC–SM	246	60 (BD, CS)	DH, DH	20.7 ± 3.5
	2013/2014	WW	229	/	DH	9.3 ± 2.1
	2014/2015	WB	150	48 (BD)	DH	8.4 ± 1.3
	2015/2016	CC–SM	203	56 (BD)	DH, DH	19.5 ± 4.2
	2016/2017	WW	198	45 (BD)	DH, CH	9.0 ± 0.7

[a] WW: Winter wheat, SM: Silage maize, WR: Winter rapeseed, WB: Winter barley, SB: Summer barley, CC: Cover crop, GM: Grain maize, SP: Spelt.
[b] BD: biogas digestate, CS: cattle slurry.
[c] P: ploughing, G: grubbing, DH: disc harrow, CH: circular harrow.
[d] For cereals, winter rapeseed and grain maize, yields are reported as grain dry matter (DM), and for silage maize as total aboveground DM.

2.2.3. Gap filling and flux partitioning

The REddyProc (Wutzler et al., 2018) web application was used to derive complete datasets for NEE, R_{ECO} and GPP in order to calculate seasonal and annual budgets. This tool applies a friction velocity filter (Papale et al., 2006) to the pre-processed 30-min fluxes as a first step. The data gaps are then filled with the average values under similar meteorological conditions using look-up tables (LUT) (Reichstein et al., 2005). The considered meteorological variables are R_g, T_a and vapor pressure deficit (VPD). The initial time window of the LUT is 7 days, which is increased to 14 days if no similar conditions are found. In this step-wise approach depending on data availability, only similar conditions of R_g are used if no T_a and VPD data are available. If none of these requirements can be fulfilled, then the mean diurnal variation method according to Falge et al. (2001) with step-wise increased window-sizes is applied until the gap is filled. To evaluate the uncertainty of the gap-filling procedure, the web application creates artificial data gaps, fills the gaps using the described algorithm, and compares them with the measured fluxes.

The day-time based approach following Lasslop et al. (2010) was used to partition the net CO_2 exchange into photosynthesis and respiration. In this approach, the activation energy parameter (E_0) in the Lloyd and Taylor (1994) model is estimated from nighttime data, whereas the respiration at base temperature (r_b) and the parameters of the hyperbolic light-response curve (Falge et al., 2001) are estimated using daytime data. This approach also accounts for the limitation of GPP at high VPD. Therefore, the maximum CO_2 uptake rate of the

canopy at light saturation (β) is replaced by an exponentially decreasing function at VPD > 10 hPa with a new parameter (k), describing the response of the maximum C uptake to VPD for time windows of four days. In contrast to the nighttime-based approach for flux partitioning (Reichstein et al., 2005), GPP and R_{ECO} derived from the daytime-based approach do not sum up to the gap-filled NEE value at each time step because they are not calculated from NEE.

2.2.4. Ogive optimization

To evaluate the contribution of low-frequency fluctuations on the EC measurements, the ogive optimization method of Sievers et al. (2015) was applied. We used the Ogive Optimization Toolbox (OOT, Version 1.0.5) coded in MATLAB® (Mathworks Inc., Boston, MA, USA). In OOT, an ensemble of usually 10,000 flux ogives is generated by perturbation of the flux averaging time and the running mean window. Both methods – adjusting the flux averaging time and subtracting a running mean from the observed signal – are established methods for filtering out low-frequency contributions while retaining the local turbulent contributions (Sakai et al., 2001; Mcmillen, 1988). Based on the resulting ogive density ensemble, a theoretical generalized co-spectral distribution model is fitted, and the best fit is regarded as the most likely local turbulent flux. For a detailed description of the ogive optimization process, see Sievers et al. (2015).

2.3. Crop parameters

During the observation period, crop development was monitored at each site in intervals of roughly four and two weeks during the non-growing season and main growing season, respectively. On five permanent plots per site, canopy height and phenological development stage were determined with ten replicates. At the beginning of shoot development, at full flowering and at the time of maturity, aboveground biomass samples were taken at each plot. At intermediate harvests, the fresh weight of the biomass was measured in the lab, and after oven drying at 60 °C the dry matter (DM) content was determined. Samples taken at final harvest were separated into vegetative and generative organs (oven drying at 30 °C until constant weight) after weighing the total fresh matter. Dried samples were ball milled and analyzed for their total C and N contents with an elemental analyzer (Vario EL, Elementar Analysensysteme, Hanau, Germany) (Högy et al., 2009; Högy et al., 2010).

We calculated the growing degree days (GDD) as a function of time (n, days) following McMaster and Wilhelm (1997) in order to characterize the growing conditions for crops in the different years and regions:

$$\sum (((T_{\max,i} + T_{\min,i})/2) - T_{base})$$

where $T_{max,i}$ (°C) and $T_{min,i}$ (°C) are the daily maximum and minimum temperature, respectively. T_{base} is the temperature from which crop growth takes place. As described in Wizemann et al. (2015), an upper threshold temperature, T_{ut}, was used, and temperatures < T_{base} were set to T_{base} and temperatures > T_{ut} were set to T_{ut}. T_{base} and T_{ut} were 0 and 37 °C for winter wheat and 10 and 30 °C for silage maize, respectively.

2.4. Net biome productivity

To calculate NBP for particular periods and sites, C fluxes related to agricultural management were added to the measured CO_2 fluxes:

$$NBP = NEE + C_{in} + C_e$$

where NEE is the gap-filled and cumulated CO_2 exchange for the respective period (kg CO_2-C ha^{-1}), C_{in} is the C input by organic fertilizers (kg C ha^{-1}) and C_{ex} is the C export via harvested biomass (kg C ha^{-1}). To estimate C_{in} and C_{ex}, information provided by the farmers, standard values and own analyses were combined. Farmers reported on the total amounts of organic fertilizers (slurry or biogas digestate) that were applied to each field in each year. To calculate C_{in}, we used well-documented standard values (TLL, 2012; LWKSH, 2013) for dry matter (DM) and C contents. To calculate C_{ex}, we used the documented yields from the farmers together with the proportions of harvest residues left on the fields. Total amounts of straw were calculated from the harvest index measured on the sampling plots at the time of harvest. If DM yields were not reported, as is generally the case for silage maize, yields were corrected for their DM contents. For this, we assumed typical values for valuable harvest products: 32% DM for silage maize, 91% DM for rapeseed and 86% DM for cereal grains (winter wheat, winter and summer barley, winter spelt). Finally, the removed biomass (grains and straw) was multiplied with its measured C content to obtain C_{ex}. It was assumed little to no C left the field due to erosion.

2.5. Statistical analyses

The software R studio (R version 3.2.4) was used to evaluate the data. Statistical tests were based on the definition of linear mixed models (Laird and Ware, 1982; Verbeke and Molenberghs, 2000). The data were assumed to be normally distributed but heteroscedastic due to the different years. These assumptions and the identification of appropriate mixed models were based on graphical residual analyses. Analyses of variance (ANOVA) were performed to identify significant effects of the factors region, site and crop as well as their interactions on the annual values of NEE and NBP. The year as an integrative parameter for the variability caused by weather characteristics was treated as a random factor. Multiple contrast tests (Bretz et al., 2011), based on the comparison of means by Tukey tests, were conducted to identify significant differences between sites, regions and crops. The relationships between cumulated GPP or NEE over particular periods and the corresponding GDD as well as ANPP were evaluated by ordinary linear regression analyses.

3. Results

3.1. Weather conditions

The two study regions differed distinctly in their weather characteristics during the 8-year study period (Fig. 2). In almost every month, the mean temperature at KR was higher than at SJ (Fig. 2a). Lowest annual mean temperatures were recorded in 2010 (8.5 °C in KR, 6.1 °C in SJ). The warmest year was 2014, with 10.9 °C in KR and 8.4 °C in SJ. The coldest month was February 2012, with −3.1 and −6.2 °C, whereas the warmest month was July 2015, with 21.2 and 18.7 °C in KR and SJ, respectively. The deviations of monthly mean temperatures from the long-term average (1981–2010) followed a very similar pattern in both regions (Fig. 2b). Concurrent with the lowest monthly mean temperatures, the most negative temperature anomalies were observed in February 2012 (−4.8 °C in KR, −5.6 °C in SJ). The most positive anomalies were also recorded in winter, with +4.2 and +3.5 °C in December 2015 for KR and SJ, respectively.

In KR, the wettest year was 2013, with a total precipitation amount of 947 mm, whereas the highest precipitation in SJ was recorded in 2017 (1056 mm). In both regions, the lowest precipitation occurred in 2015 with 682 and 761 mm in KR and SJ, respectively. In KR, the highest monthly precipitation occurred in August 2010 (157 mm), December 2011 (162 mm) and May 2013 (169 mm). Highest monthly precipitation in KR was 186 mm in July 2011, 187 mm in July 2014 and 189 mm in July 2017 (Fig. 2c). Very dry months occurred mainly in autumn and winter, with lowest precipitation in November 2011 (7 and 5 mm in KR and SJ, respectively) and December 2016 (9 mm in both KR and SJ). Compared to the temperature anomalies, the temporal pattern of precipitation anomalies was less similar between the two regions (Fig. 2d). However, the above-mentioned months with highest and

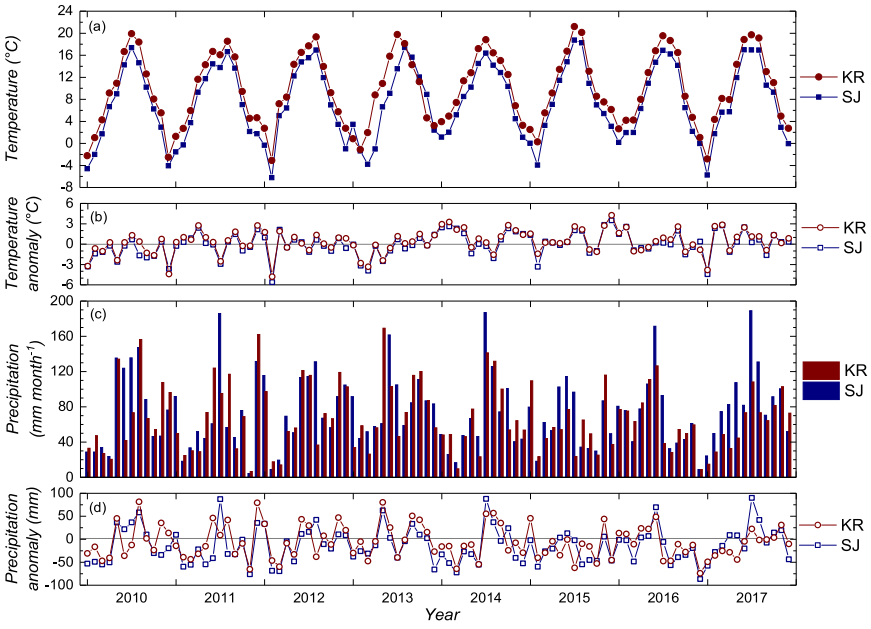

Fig. 2. Weather and climate.
Monthly temperatures and precipitation over the period 2010–2017 in the two study regions Kraichgau (KR) and Swabian Jura (SJ). (a) Mean monthly temperature, (b) difference between monthly mean temperatures and climatological 30-yr means (1981–2010), (c) monthly precipitation, and (d) difference between monthly precipitation and climatological 30-yr (1981–2010) mean monthly precipitation.

lowest precipitation also showed the highest deviations from the long-term mean monthly value. Anomalies ranged from −74 mm (December 2016) to +82 mm (August 2010) in KR and from −87 mm (December 2016) to +90 mm (July 2017) in SJ.

3.2. CO_2 measurements and budgeting

3.2.1. Variability of CO_2 exchange

Depending on the region, the time of year and the crop, the pattern of mean diurnal CO_2exchange rates differed substantially (Fig. 3). As winter wheat was never seeded before October and harvested not later than August, there are no measurements over winter wheat in September. During this time, winter rapeseed seeded in August had already emerged, and distinctive CO_2 fixation rates up to monthly mean values of −1.73 (KR) and −1.05 kg CO_2-C ha^{-1} 30 min^{-1} (SJ) occurred in October. The CO_2 exchange of winter rapeseed and winter wheat in April revealed two regional differences between KR and SJ. Firstly, the diurnal patterns of the two crops were similar in KR, while in SJ the daytime NEE of winter wheat was substantially higher (i.e., more negative), with a 2-fold mean maximum net CO_2 uptake at midday compared to winter rapeseed. Secondly, maximum daytime NEE of both winter rapeseed and winter wheat were higher in KR than in SJ. Both crops reached their maximum mean monthly net CO_2 fixation rates in May, with −4.28 and −4.48 kg CO_2-C ha^{-1} 30 min^{-1} for winter rapeseed and −6.16 and −5.76 kg CO_2-C ha^{-1} 30 min^{-1} for winter wheat in KR and SJ, respectively. Thus, the CO_2 uptake capability was higher for winter wheat in KR, while the opposite held true for winter rapeseed. Also regarding the nighttime CO_2 release, regional differences were documented for winter rapeseed: the maximum monthly nighttime NEE was 1.63 in KR and 1.98 kg CO_2-C ha^{-1} 30 min^{-1} in SJ, both recorded in June. Also over winter wheat, the monthly peaks of CO_2 release occurred in June but were slightly higher in KR (1.59) compared to SJ (1.36 kg CO_2-C ha^{-1} 30 min^{-1}). The mean diurnal courses in July reveal that the daytime CO_2 uptake of winter rapeseed and winter wheat decreased earlier in KR than SJ.

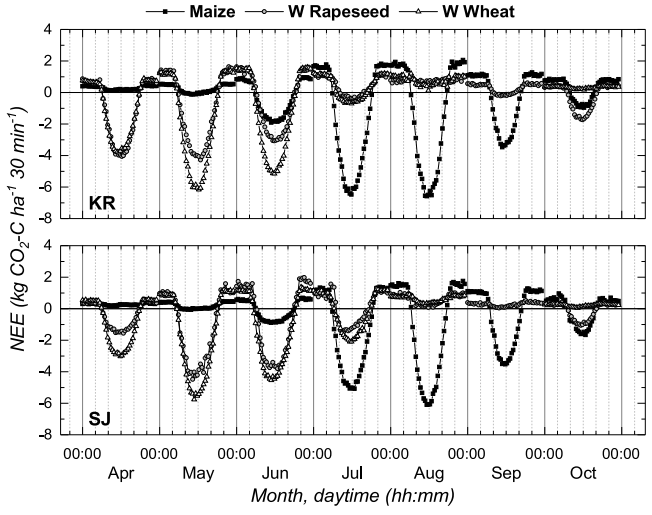

Fig. 3. NEE variability.
Mean diurnal courses of net ecosystem exchange (NEE) on a monthly basis for the main growing season of maize, winter rapeseed and winter weed in the two study regions Kraichgau (KR) and Swabian Jura (SJ). Number of site years averaged for maize, winter rapeseed and winter wheat: 7, 4 and 13 in KR and 8, 2 and 7 in SJ, respectively.

The annual pattern of CO_2 exchange measured over the maize canopies showed a 3-months shift compared with winter rapeseed and winter wheat (Fig. 3). As observed for the other two crops, the maize plants in KR showed higher maximum CO_2 fixation and respiration rates at the beginning of the productive phase (June). In SJ, these rates were higher at the end of the growth period (October). Maximum monthly mean fluxes for maize were recorded in August in both regions: −6.58 and 2.06 kg CO_2-C ha^{-1} 30 min^{-1} in KR and −6.09 and 1.76 kg CO_2-C ha^{-1} 30 min^{-1} in SJ.

Beyond the crop-specific effects on CO_2 exchange patterns (Fig. 3), inter-site and inter-annual variability was large, as evident from the cumulative NEE from 1 April to harvest for the 20 site-years of winter wheat cropping (Fig. 4). At the time of winter wheat harvest, the mean cumulative NEE was −4960 kg CO_2-C ha^{-1}. The lowest and highest uptakes were −2360 (EC3 2017) and −6460 kg CO_2-C ha^{-1} (EC1 2011), respectively. Over the first three months (April–June), the cumulative NEE (NEE_{cum}) steadily decreased. After reaching an inflexion point, NEE_{cum} increased until harvest. Thus, maximum net CO_2 uptake was between 369 (EC1 2015) and 1340 kg CO_2-C ha^{-1} (EC3 2014) higher compared to NEE_{cum} at the time of harvest. In SJ, winter wheat was harvested later than in KR throughout the study period. Earliest and latest harvest dates were 20 July (EC1 2015) and 7 August (EC2 2013) in KR and 11 August (EC4 2015/EC6 2017) and 26 August (EC5

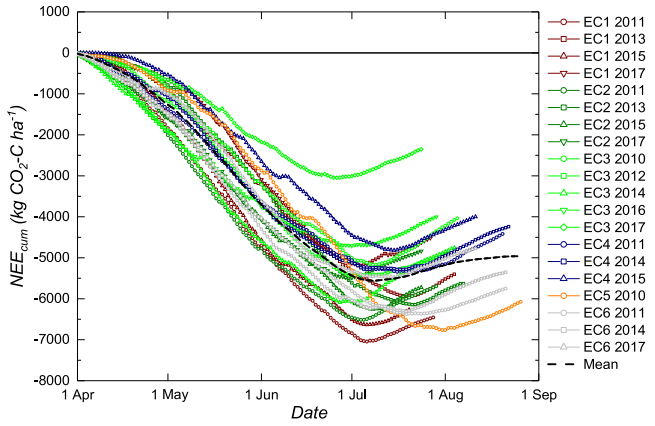

Fig. 4. Cumulative NEE.
Variability of cumulative net ecosystem exchange (NEE) for the observed 20 site-years of winter wheat from 1 April until harvest.

2010) in SJ, respectively. Finally, the time span between maximum cumulative CO_2 uptake and the harvest date was on average six days longer in SJ (30 d) than in KR (24 d).

3.3. Annual carbon budgets

The single components of the site- and year-specific C budgets are summarized in Table 3. In general, C_{ex} was lower at winter rapeseed sites, while the whole-crop harvest of silage maize resulted in very high C removals. Due to the very similar crop rotations on the KR sites, mean annual C exports were also similar, whereas the differences on the SJ sites were more pronounced, particularly between EC4 and the other two sites. The annual budgets of NEE were extremely variable. This is underlined by the minimum and maximum NEE in KR, observed for the same site in two consecutive years (EC1 2011 and 2012). In SJ as well, annual NEE varied from strongly negative (EC6 2012) to positive (EC4 2016). Note that for those years in which winter wheat was cropped, annual NEE was distinctively negative in 18 out of 20 site years. Interestingly, the two successive winter wheat years 2016 and 2017 at EC3 showed net CO_2 losses of almost the same magnitude. As for NEE, the annual budgets of the net biome productivity (NBP) also showed a high variability, with similar ranges in both regions (-3290–7650 kg C ha^{-1} yr^{-1} in KR and -3970–7320 kg C ha^{-1} yr^{-1} in SJ). Averaged over the study period, all six sites were net C sources with comparable mean annual emissions of around 1000 kg C ha^{-1}. The exception is EC3 with mean annual losses of 2000 kg C ha^{-1}.

The ANOVA showed no significant effects of region, site or their interaction on the annual NEE or NBP. Consequently, no significant differences between the NEE and NBP of the two regions or any of the six sites were detected based on the comparison of means. Crop-specific effects were evaluated using a linear mixed model that considered the crop effect as fixed for both NEE and NBP. Only crops grown in more than two years were considered (silage maize, winter barley, winter rapeseed, winter wheat). The different sites were considered as random effect. The ANOVA confirmed a highly significant effect ($p \leq 0.001$) of crops on NEE and NBP. The model explained 53% (NEE) and 65% (NBP) of data variability. The annual NEE of winter rapeseed was significantly higher than that of winter barley and winter wheat. Moreover, the NEE of silage maize was lower than that of winter rapeseed, although the difference was not significant ($p = 0.08$). In contrast, the comparison of means revealed a significantly higher annual NBP of silage maize compared to the other three crops, with $p \leq 0.01$ for winter rapeseed and $p \leq 0.001$ for winter barley and winter wheat. The budgets of the other three crops did not differ significantly (Fig. 5).

3.4. Effect of low-frequency contributions to CO_2 flux

Applying the ogive optimization method filtered out low-frequency contributions. For reasons of comparability, the OOT fluxes were computed for the same month (June 2015) at all sites and compared to

Table 3
Annual carbon budgets of the six study sites. NEE: net ecosystem exchange of CO_2, C_{in}: carbon input by organic fertilizers, C_{ex}: carbon export via harvest, NBP: net biome productivity.

Site	Component	2010	2011	2012	2013	2014	2015	2016	2017[a]	Mean
		(kg C ha^{-1} yr^{-1})								
EC1	NEE	−2836	−6543	2398	−3730	−3940	−4216	−2087	−2974	−2991
	C_{in}	−756	0	0	−1120	0	−720	0	0	−324
	C_{ex}	5716	3254	2444	4622	7232	3010	3309	2739	4040
	NBP	**2123**	**−3289**	**4843**	**−228**	**3292**	**−1926**	**1222**	**−238**	**725**
EC2	NEE	523	−2303	/[b]	−4360	−3323	−3963	−1244	−2952	−2517
	C_{in}	0	0	−700	0	0	−720	0	0	−177
	C_{ex}	2042	3470	7726	2622	6892	3780	1716	3733	3998
	NBP	**2565**	**1167**	/	**−1737**	**3569**	**−903**	**472**	**782**	**845**
EC3	NEE	−2840	−326	−4324	−2132	−4297	−2048	1487	1429	−1631
	C_{in}	0	0	0	0	0	0	0	−280	−35
	C_{ex}	2768	7974	3024	2218	2958	6531	2335	2101	3739
	NBP	**−72**	**7648**	**−1300**	**86**	**−1339**	**4483**	**3822**	**3251**	**2072**
EC4	NEE	−784	−2477	−1856	−776	−2910	−2697	1081	−2942	−1670
	C_{in}	0	0	0	0	0	0	−280	−560	−105
	C_{ex}	1524	3228	3208	634	3163	2898	2121	6453	2904
	NBP	**740**	**751**	**1352**	**−142**	**252**	**200**	**2922**	**2951**	**1128**
EC5	NEE	−4906	−1191	−3395	−3226	−4323	−3981	/[b]	−4398	−3632
	C_{in}	−280	−400	−1200	−720	−1200	0	0	−1600	−675
	C_{ex}	3089	8915	7381	4046	3831	7007	7462	4693	5803
	NBP	**−2097**	**7324**	**2787**	**100**	**−1692**	**3015**	/	**−1305**	**1163**
EC6	NEE	−2723	−5156	−6290	−1666	−3996	−1140	−1056	−3229	−3157
	C_{in}	−840	−420	−1120	−1000	0	−1600	−616	−1240	−854
	C_{ex}	6063	3454	3438	8275	6502	2571	7783	3225	5164
	NBP	**2500**	**−2122**	**−3972**	**5609**	**2506**	**−169**	**6111**	**−1243**	**1152**

[a] No full annual budgets for NEE and NBP. End of datasets in 2017: EC1: 26 September, EC2: 24 October, EC3: 24 October, EC4 – 6: 3 November.
[b] No NEE measurement during most of the growing season. EC2 2012: Malfunction of the CSAT3; EC5 2016: CSAT3 and LI-7500 damaged due a tractor accident.

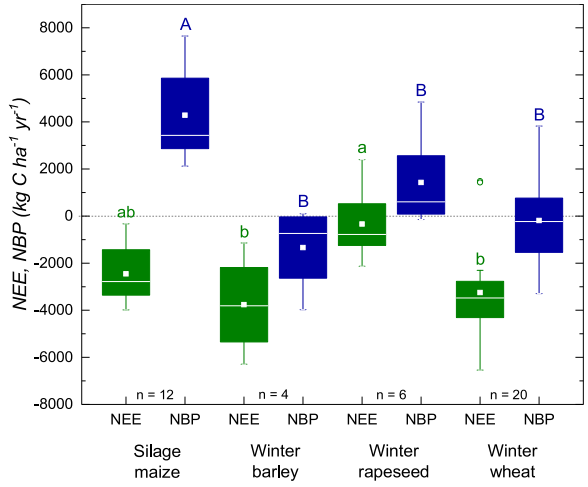

Fig. 5. Budgets.
Annual budgets of net ecosystem exchange (NEE) and net biome productivity (NBP) for the harvest years (January − December) of the four most frequently grown crops on the six study sites. Different lowercase and capital letters indicate significant differences between the mean NEE and NBP of the different crops, respectively ($p \leq 0.05$).

the conventional 30-min fluxes. Over this period, all sites showed a net uptake of CO_2 although the magnitudes differed depending on crop type. Additionally, months with net CO_2 release (when no crop was present) were selected (Fig. 6). The mean diurnal courses reveal that the OOT fluxes are less scattered and thus daily dynamics are more steady, particularly during nighttime. In most cases, the OOT daytime fluxes shifted towards slightly higher absolute values, irrespective of flux direction. In contrast, almost no effects were found for daytime fluxes in June 2015 at EC3 and EC5. Nevertheless, the mean monthly flux for June 2015 decreased at most sites except for EC3 (i.e., the net uptake of CO_2 increased). The relative change ranged from −32% at EC5 to +2% at EC3. For those months with net CO_2 release, the effect of eliminating low-frequencies was less systematic, but yielded a higher mean flux at four out of the six sites. The relative change of mean monthly NEE as a result of ogive optimization ranged from −3% (EC3 and EC5) to +13% (EC4).

3.5. Controlling factors of CO_2 exchange

No significant relationship was found between the GDD from 1 April until the harvest of winter wheat and the cumulative NEE or GPP of winter wheat for these periods (Fig. 7a, b). Moreover, no distinct differences between the GDD of the two regions were evident when accumulated until the day of harvest. Contrastingly, significant relationships were found when only April and May were considered, with a stronger relationship between GDD and GPP (Fig. 7c, d). A higher GDD in April/May was observed in KR compared to SJ, with mean values of 671 and 565 °C, respectively. Relationships between GDD and the CO_2 exchange were stronger in KR than in SJ (Table 4). Nonetheless, the coefficient of correlation between the GDD in April/May and the NEE was comparable for both regions, while a stronger relationship with GPP was found in KR, but a much weaker one in SJ.

To investigate the relationship between crop growth dynamics and CO_2 exchange, we related the observed C accumulation in aboveground biomass during a particular period to measured and gap-filled NEE and simulated GPP for the same period and all available site years (Fig. 8). As indicated by the slope of linear regression, the measured net CO_2-C exchange above the canopy was roughly 50% of the aboveground net primary production (ANPP) of the crops (Fig. 8a). The coefficient of correlation (r) and the adjusted coefficient of determination (Adj. R^2) suggested a rather strong relationship. Separating the data for the two regions showed an even closer relationship in KR, but a weaker one in SJ, while the slope of linear regression remained almost constant (Table 4). The same result was obtained for GPP *vs*. ANPP, while the relationship was closer compared to NEE *vs*. ANPP in each case. For the whole dataset, the slope of linear regression indicated that an additional 75% of photosynthetically fixed C was necessary to generate a certain amount of C in crop tissues (Fig. 8b). Regarding the individual regions, the relationship was clearly closer in KR than in SJ; the slope of

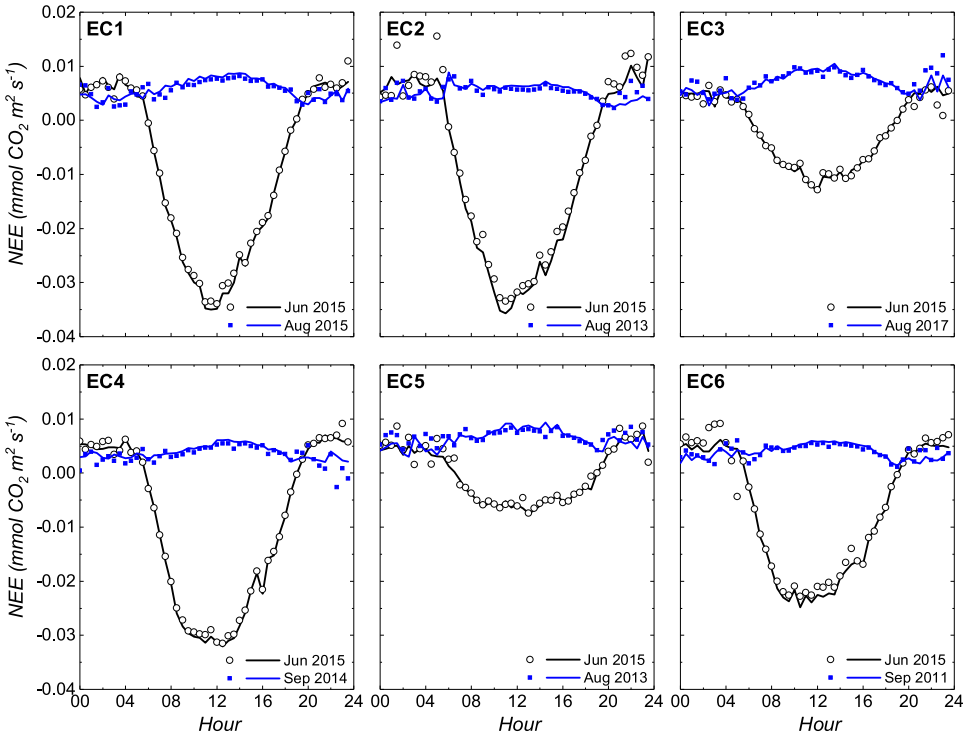

Fig. 6. Low-frequency contributions.
Monthly mean diurnal courses of net ecosystem exchange (NEE) of fully developed canopies (black) and fallow periods (blue). NEE computed based on conventional 30-min averaging interval (symbols) and ogive optimization method (OOM, lines). The OOM filters out low-frequency flux contributions.

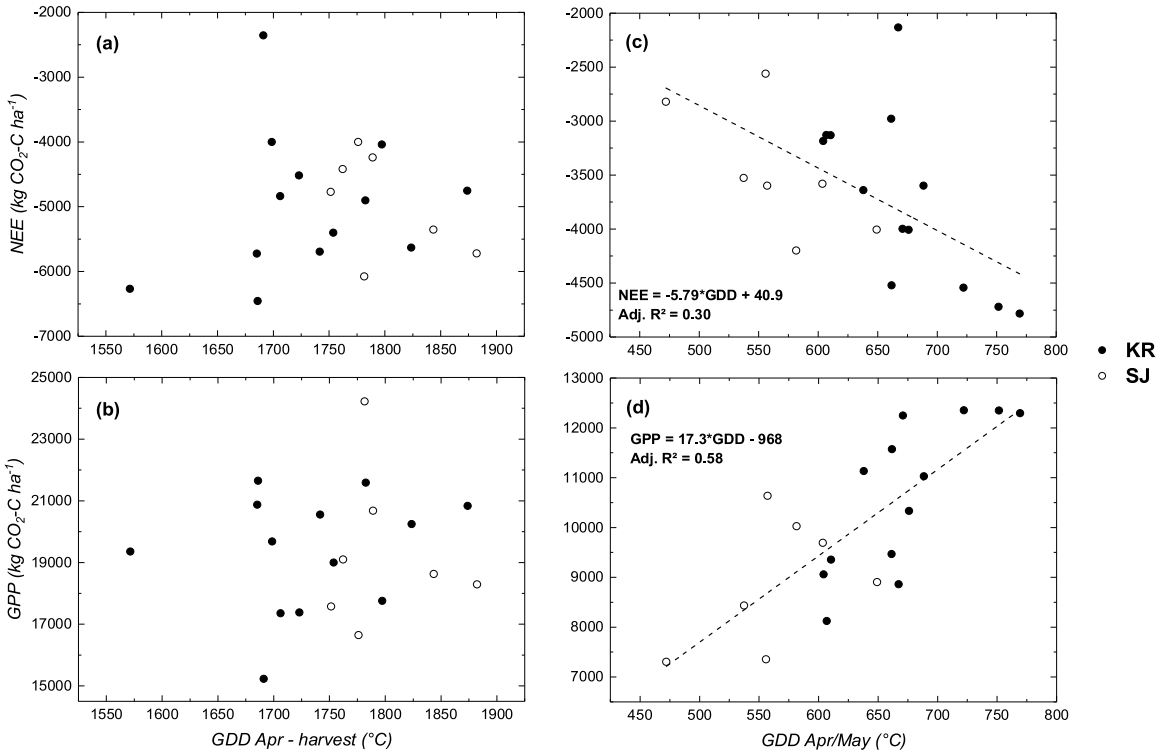

Fig. 7. Growing degree days.
Correlation between net ecosystem exchange (NEE) and growing degree days (GDD), and gross primary productivity (GPP) and GDD measured in Kraichgau (KR, full circles) and Swabian Jura (SJ, open circles). Scatterplots based on 20 site-years of winter wheat seasons. Panels (a) and (b) evaluate the period 1 April until harvest. Panels (c) and (d) evaluate the months April and May (main growing period).

Table 4
Linear regression of growing degree days (GDD) in April and May (°C) versus net ecosystem exchange (NEE) of CO_2 (kg CO_2-C ha^{-1}) and gross primary production (GPP, kg CO_2-C ha^{-1}) for the same period of the 20 site − years with winter wheat cropping, as well as the measured aboveground net primary production (ANPP, kg C ha^{-1}) versus NEE and GPP for all site − years with sufficient data availability (46).

Linear regression	Kraichgau				Swabian Jura			
	Slope	Intercept	Pearson's r	Adj. R^2	Slope	Intercept	Pearson's r	Adj. R^2
NEE *vs.* GDD A/M	−10.5	3359	−0.69	0.42	−6.93	446	−0.65	0.30
GPP *vs.* GDD A/M	22.4	−4403	0.77	0.56	11.5	2413	0.49	0.09
NEE *vs.* ANPP	−0.51	−418	−0.81	0.65	−0.50	−530	−0.71	0.48
GPP *vs.* ANPP	1.86	3748	0.92	0.84	1.48	5175	0.63	0.37

linear regression increased for the KR data, but decreased for SJ compared to the complete dataset. Both regressions for ANPP yielded a higher absolute intercept for SJ compared to KR (Table 4).

4. Discussion

4.1. Methodological aspects

Long-term experiments in German croplands showed no significant depletion of SOC under constant management (Körschens et al., 2014). In contrast, C budgets based on measuring the CO_2 exchange above the crop canopy over shorter periods (e.g., Kutsch et al., 2010; Prescher et al., 2010; Schmidt et al., 2012; Buysse et al., 2017) consistently revealed net C losses from agroecosystems. Although we observed slightly decreasing SOC concentrations in the top soils at four of our six study sites, the annual concentration change was not significantly different from zero (Table 1). At EC6, a significant increase in SOC concentration was observed. It has to be noted, however, that these measurements were based on three permanently installed plots at each study site. Due to the generally high spatial variability of SOC, the number of plots was probably not sufficient to represent this variability on the large study sites. Skinner and Dell (2014) demonstrated that C budget estimates based on EC and soil core measurements can differ substantially and comparing both methods is challenging. As EC is the state-of-the-art method for analyzing the spatially integrated ecosystem-scale C exchange, we will focus our discussion on the results obtained by EC.

Depending on site and weather conditions, winter-time CO_2 fluxes might contribute significantly to annual NEE (Buysse et al., 2017). Importantly, by generating two full-year datasets at sites EC2 and EC6, we were able to quantify the contribution of cumulated NEE during the period without measurements at the other four sites to the annual NEE budgets. Clearly, the proportion of NEE during a certain period on annual NEE becomes greater the more one component, GPP or R_{ECO}, dominates during that period. Our measurements demonstrated that winter-time CO_2 exchange can generally be regarded as being balanced. The exception is distinctively warm periods combined with the absence of assimilating vegetation cover and thus dominated by R_{ECO}.

The approach of filling missing winter measurements by using the parameterizations from Lasslop et al. (2010) for the periods before and after the gaps yielded in most cases equal or even smaller mean residuals compared to parameterizations based on winter data (Figs. S1 and S2). We argue that the residue analysis presented here

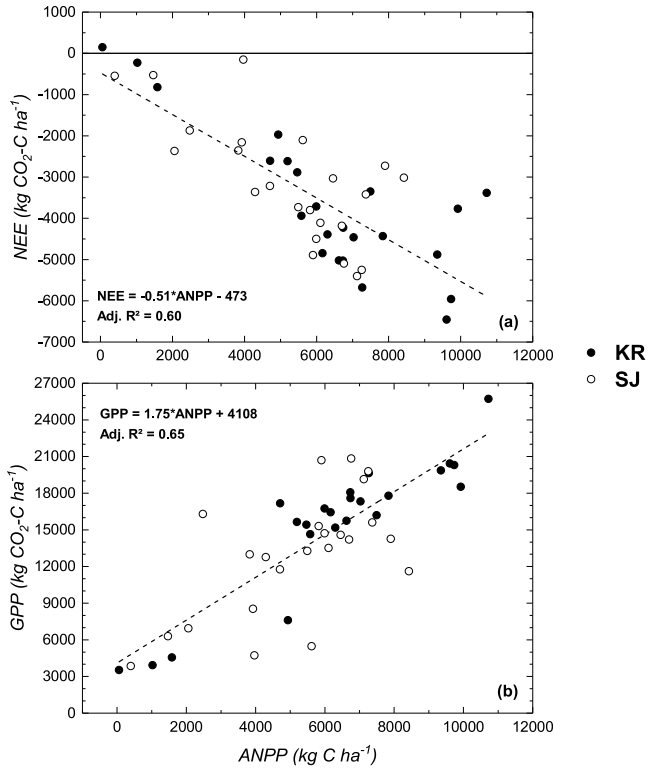

Fig. 8. Aboveground net primary production.
Relationship between (a) net ecosystem exchange (NEE) and aboveground net primary production (ANPP) and (b) gross primary productivity (GPP) and ANPP. Figures created based on all available site-years for Kraichgau (KR) and Swabian Jura (SJ).

demonstrated the validity and usability of this gap-filling approach, although the periods without measurements should be kept as short as possible. The onset of the growing season was identified as being the determining period for the total annual CO_2 budget. This makes it important to obtain reliable measurements during this transition period (Poyda et al., 2017).

For selected periods, the ogive optimization method demonstrated that the contribution of low-frequency fluctuations explained part of the scatter often observed for fluxes averaged over 30 min, particularly at night (Fig. 6). As postulated by Sievers et al. (2015), relative differences between conventionally calculated and ogive-optimized fluxes tended to be higher when flux values were small. However, on a monthly basis, over- and underestimation of the ogive optimization method outbalanced each other. This led to negligible total effects, particularly during periods without CO_2 uptake. Importantly, the method eliminated implausible outliers from the dataset that might, in some cases, affect CO_2 budgets, such as for example in June 2015 at EC2 and in September 2014 at EC4. Finally, fluxes driven by low-frequency fluctuations can legitimately be disregarded when the aim of the research is to link fluxes to local site or management activities. Particularly under non-stationary conditions, the EC method systematically fails to capture both high and low frequencies at the same time (Kidston et al., 2010), further supporting the notion of neglecting low-frequency fluctuations.

As the state-of-the-art approach, we used the widely-accepted WPL correction for density effects due to water vapor and heat transfer on CO_2 fluxes (Webb et al., 1980). As this approach only accounts for density fluctuations of dry air, Liu (2005) raised concerns about the suitability of the WPL correction for ecosystems where water vapor significantly contributes to air density fluctuations. In agroecosystems with high transpiration rates of the crop canopy, latent heat fluxes are generally high, with Bowen ratios well below unity during the main growing season (Wizemann et al., 2015). By applying an alternative approach that accounts for density fluctuations in both dry air and water vapor, Liu (2005) obtained a 26% larger C sink during the growing season at a spruce forest stand in Alaska. This resulted from higher CO_2 uptake during the day and lower respiration rates at night compared to the WPL correction. Although boreal spruce forests and temperate agroecosystems differ distinctly, water vapor density fluctuations are likely to have a substantial effect on measured fluxes at our study sites as well. Thus, the applied WPL correction might have underestimated the C sink or overestimated the C source activity at our sites. In the light of the debate on the validity of the different concepts (Kowalski, 2006; Liu, 2006), we applied the standard WPL correction to our dataset.

4.2. Characteristics of CO_2 exchange patterns

Although no systematic differences were recorded between the annual CO_2 budgets of the two study regions KR and SJ, the temporal dynamics over the course of the year differed distinctly due to different pedoclimatic conditions. The higher elevation in SJ was reflected in generally lower temperatures, and the growing season started 2–3 weeks later in the year. This was the case in each of the eight years, with the most pronounced shift in the period March – July 2013 (Fig. 2a). As the GDD in spring significantly affected photosynthetic activity (Fig. 7), the lower net CO_2 uptake (Fig. 3) most likely reflected the lower temperatures in SJ. When calculated for the period 1 April until final harvest, however, the GDD showed no significant differences between the regions, and no relationship with GPP or NEE was found. This can be explained by the later harvest in SJ. Thus, the later onset of the growing season in SJ is compensated by later harvest dates, reaching similar GDD as in KR.

While the mean diurnal course of NEE above winter wheat was similar in both regions in June, daily CO_2 uptake rates in July were much higher in SJ. This reflects the high summer temperatures in KR, accelerating ripening of the wheat plants (Dietiker et al., 2010), while the milder summers in SJ allow the crops to conduct photosynthesis and to accumulate biomass over a longer period. Thus, at our study sites, the theoretical approach of calculating GDD following McMaster & Wilhelm (1997) does not give a valid proxy for CO_2uptake until maturity. This is because, firstly, no heat stress is considered and, secondly, photosynthesis is low during the ripening phase when assimilates are re-allocated to the storage organs (even though GDD might be very high during this period).

Multi-site studies have revealed that net C losses from arable fields tend to be higher at sites with high soil C contents (Kutsch et al., 2010). The results of our study did not confirm this (compare Tables 1 and 3): we observed no general trend towards higher respiration at the C-rich SJ sites. Note, however, that respiration measured by the EC method is the sum of heterotrophic and autotrophic respiration, making it difficult to separate the two processes. Higher nighttime CO_2 release could therefore reflect higher productivity and thus crop respiration rather than higher soil respiration. This is underlined by a very close relationship between the annual sums of GPP and R_{ECO} (slope = 1.03, $r = 0.91$), as was also shown in other studies (e.g., Gilmanov et al., 2014).

At the three KR sites, Demyan et al. (2016) used chamber respiration measurements on vegetated and bare fallow plots to separate the different components of R_{ECO} from EC measurements. They estimated that heterotrophic respiration accounted for an average 31% of R_{ECO} under winter wheat. No such estimate was available for SJ. The relationship between the annual R_{ECO} and GPP, however, showed the same strength for both regions ($r = 0.89$), while for SJ the linear regression showed a slightly larger slope (0.99 compared to 0.95 for KR) and a much lower intercept (53 compared to 2470 kg CO_2-C ha^{-1} yr^{-1} for KR). This indicates that the proportion of heterotrophic respiration from total R_{ECO} was lower at the SJ sites despite their higher SOC

contents. Along the same line, Ali et al. (2018) reported that specific soil respiration (g^{-1} SOC) and potential enzyme activities were higher in KR *vs*. SJ soil samples. While microbial biomass significantly explained soil respiration in SJ, the SOC content was the most important factor in KR. These results suggest that the abiotic conditions for microbial growth limited SOC decomposition in SJ, while substrate availability limited it in KR. Thus, the colder and wetter climate in SJ presumably reduced soil microbial activity due to lower soil temperatures and temporarily high soil moisture contents.

The relationships between the ANPP and the NEE and GPP (Fig. 8) provided insights into the proportions of fixed C accumulated in aboveground crop biomass. The linear regression slopes revealed that the gross photosynthetic C uptake was on average 75% higher, while the net C uptake was 50% lower than the C accumulation in aboveground crop biomass over a given period. The intercept from GPP *vs*. ANPP illustrated that, on average, roughly 4100 kg CO_2-C ha^{-1} were fixed without any aboveground C enrichment. This was due to autotrophic respiration in the same magnitude or a pronounced below ground C allocation. Nonetheless, measurements with low ANPP were made during the ripening phase, and annual, highly cultured crops are mainly allocating assimilates to their generative organs at this stage, resulting in low fractions of belowground net primary production (fBNPP) (Loges et al., 2018; Pausch and Kuzyakov, 2018).

While the negative intercept of NEE *vs*. ANPP suggests that BNPP exceeded R_{ECO} during periods with no ANPP, this finding may reflect the variable dataset involving different crops and periods covered. Time series with ANPP close to zero were available only for winter wheat. The wheat-specific linear regression of NEE *vs*. ANPP showed an intercept of 622 kg CO_2-C ha^{-1}, supporting the aforementioned assumption that BNPP is also very low during these periods. Interestingly, the wheat-specific analysis of GPP also yielded in a different picture compared to the whole dataset. For winter wheat, each kg of C in ANPP was related to 2.2 kg C fixed by photosynthesis, indicating that the sum of autotrophic respiration and BNPP was more than twice the ANPP. This slope was only 1.55 for maize, illustrating the potentially higher C use efficiency (CUE) of C4 crops (Choudhury, 2001).

Beyond these crop-specific differences, regional characteristics were also observed (Table 4). The lower slope of GPP *vs*. ANPP at the SJ sites potentially reflects less root growth due to the low solum thicknesses and a higher water availability in top soil layers compared to KR. Furthermore, lower autotrophic respiration due to lower temperatures in SJ likely contributed to the observed higher mean CUE (Choudhury, 2001). The much weaker relationship in SJ than in KR represented the higher variability in site and weather conditions as well as the crops grown there. More research is needed to provide more detailed insights into the plant functional traits of different crops, particularly under variable environmental conditions. These future efforts should combine highly resolved measurements of above- and belowground net primary production (NPP), ecosystem scale fluxes and flux partitioning as well as isotopic labeling (Riederer et al., 2015).

4.3. CO_2 and carbon budgets

4.3.1. NEE

Annual NEE showed a distinct variability and ranged from −6540 to 2400 kg CO_2-C ha^{-1} yr^{-1}. Interestingly, minimum and maximum NEE were observed in two consecutive years on the same site (EC1 2011 and 2012) cropped with winter wheat and winter rapeseed, respectively. Our results emphasize that the inter-annual variability of CO_2fluxes clearly outweighed site-specific effects in these intensively managed crop rotations. The mean annual NEE from the six study sites and the eight-year observation period was −2580 kg CO_2-C ha^{-1} yr^{-1}, with a site-specific range between −1630 (EC3) and −3630 kg CO_2-C ha^{-1} yr^{-1} (EC5). This result corresponds well with the mean annual NEE of −2400 kg CO_2-C ha^{-1} yr^{-1} reported by Kutsch et al. (2010) for a four-year observation period on seven European crop sites with site-specific means between −1470 and −4610 kg CO_2-C ha^{-1} yr^{-1}. Schmidt et al. (2012) conducted EC measurements over a winter wheat field in western Germany and observed a constant NEE of −2700 kg CO_2-C ha^{-1} yr^{-1} during two consecutive years. This is very close to the mean annual NEE of −2920 kg CO_2-C ha^{-1} yr^{-1} for 13 winter wheat site-years on European croplands measured by Ceschia et al. (2010).

In the present study, the mean annual net CO_2 uptake from 20 site-years of winter wheat cropping was −3250 kg CO_2-C ha^{-1} yr^{-1}.The variability, however, was large, ranging from very high net uptakes to net losses in 2016 and 2017 on EC3. As these two years showed the overall lowest wheat yields, crop productivity seems to be the major factor controlling net CO_2 budgets on our study sites. This was underlined by the results of the statistical analysis, indicating no significant effects of region or site on NEE. Weather conditions, however, indirectly affected CO_2 exchange by determining the variability of crop growth. This effect, for example, was evident in the two winter barley years on EC6, showing a high variability with NEE of −6290 kg CO_2-C ha^{-1} yr^{-1} in 2012 and −1140 kg CO_2-C ha^{-1} yr^{-1} in 2015. Crop rotational effects can be excluded in this case because the rotation was constant at EC6, with winter wheat preceding winter barley and cover crops being seeded after harvest. Thus, the weather conditions most likely explain this huge difference in annual NEE: 2015 was the driest and second warmest year of the observation period. This resulted in the highest annual R_{ECO} observed in SJ, while GPP was slightly reduced compared to 2012.

Beside these occasional strong inter-annual deviations for the same crops, the predominant crop effect on NEE was particularly pronounced for winter rapeseed, i.e. no significant differences were observed between the mean NEE of the other main crops (Fig. 5). Those years with winter rapeseed harvest were characterized by the lowest mean net CO_2 uptake (−336 kg CO_2-C ha^{-1} yr^{-1}), and two out of six years showed net CO_2emissions. In contrast, Ceschia et al. (2010) reported a rather high net uptake of −3060 kg CO_2-C ha^{-1} yr^{-1} for a winter rapeseed year on a site in eastern Germany. On a cropland in France, Béziat et al. (2009) measured an NEE of −2860 kg CO_2-C ha^{-1} yr^{-1} over winter rapeseed; this was slightly lower than over winter wheat, but distinctly higher compared to maize. At our study sites, the monthly patterns of mean diurnal CO_2 exchange (Fig. 3) clearly indicated a lower CO_2 uptake capacity of winter rapeseed compared to winter wheat and silage maize in both regions, whereas the nocturnal CO_2release was similar or higher. Our results support the findings of Moors et al. (2010), who emphasized that crop choice is the most important factor determining the magnitude of cropland CO_2 exchange.

In interpreting annual NEE, note that budgets were calculated for calendar years in order to compare periods of similar length. Thus, some of the variability likely reflects different conditions after harvest of the main crop (and in the case of summer crops, also before seeding). When NEE was cumulated from seeding until harvest, the relative variability decreased for the summer crops silage maize (from 46 to 29%) and spring barley (from 379 to 12%). In contrast, relative variability increased from 50 to 78% for winter barley and from 57 to 67% for winter wheat when NEE was calculated from seeding until harvest. The very high variability of winter rapeseed decreased from 432 to 155% of mean NEE. These results illustrate the great importance of the non-growing season CO_2 exchange on annual NEE budgets. As the growing season is particularly short for summer cereals such as spring barley, the non-growing season strongly determines its annual C budgets (Prescher et al., 2010).

The higher variability in cropping period budgets of winter cereals might be a result of different seeding dates between the regions and years, combined with a variable pre-winter development of crops depending on weather conditions. As the growth rates of winter cereals are generally low in autumn, R_{ECO} often dominates NEE (Béziat et al., 2009). For instance, mean gap-filled daily NEE in October was 7.7, 12.5 and −8.2 kg CO_2-C ha^{-1} d^{-1} for winter barley, winter wheat and winter rapeseed, respectively. This reflects the differences in seeding

dates, with highest net emissions for the generally later seeded winter wheat. Accordingly, conditions controlling heterotrophic respiration can strongly impact NEE during these periods and therefore also the variability of C budgets. Mild temperatures during the non-growing season, in combination with moderate amounts of rainfall and readily available substrates from harvest residues, probably enhanced microbial activity in the soil and therefore increased non-growing season C losses (Ali et al., 2015).

4.3.2. NBP

In the present study, the mean annual NBP from 46 site-years was 1190 kg C ha^{-1} yr^{-1}, which was somewhat higher than the average 950 kg C ha^{-1} yr^{-1}observed by Kutsch et al. (2010) on seven European sites. With a standard deviation (SD) of 2690 kg C ha^{-1} yr^{-1}, the variability on our sites was large, and the cultivated crop was the most important factor explaining this variability. Statistical analysis of annual NBP, however, was limited by the huge differences in the number of available years for the different crops. Nonetheless, mean annual NBP showed distinct differences among the observed crops, from net C gains to high net C losses. For winter cereals, a negative to neutral mean annual NBP was observed: −1690 kg C ha^{-1} yr^{-1} for spelt ($n = 1$), −1340 ± 1860 kg C ha^{-1} yr^{-1} for winter barley ($n = 4$) and −190 ± 1860 kg C ha^{-1} yr^{-1} for winter wheat ($n = 20$). Winter rapeseed lost on average 1430 ± 1930 kg C ha^{-1} yr^{-1} ($n = 6$), while the late covering (summer) crops such as grain maize ($n = 1$), spring barley ($n = 2$) and silage maize ($n = 12$) lost 1220, 2140 ± 1110 and 4280 ± 1920 kg C ha^{-1} yr^{-1}, respectively. In contrast, Kutsch et al. (2010) reported net C losses of 1780 kg C ha^{-1} yr^{-1} for winter wheat years, and during the two-year study of Schmidt et al. (2012) the NBP of wheat was even higher, with losses of 2460 and 2010 kg C ha^{-1} yr^{-1}. Sites with winter rapeseed lost slightly lower amounts of C (1090 kg C ha^{-1} yr^{-1}) in the study of Kutsch et al. (2010). Those authors reported almost exactly the same high C losses for silage maize years (4300 kg C ha^{-1} yr^{-1}).

While the NEE is affected by crop- and soil-specific CO_2 exchange patterns as well as weather-induced inter-annual variability, the variability of NBP is additionally controlled by management-related C fluxes. On our study sites, the share of C inputs in total NBP was relatively low (overall mean: 4.3%) when absolute values of NBP components were summed up. Only in a single year (EC6 2015) was a share of 30% reached due to very high organic fertilizer inputs. The NBP was mainly controlled by the amount of C export via harvest, with NBP increasing as the ratio of exported to imported C (C_{ex}/(NEE + C_{in})) increased (Fig. 9). Sites acted as C sources when this ratio reached values greater 1. For the main crops observed, the ratio was 0.8 (winter barley), 0.9 (winter wheat), 1.3 (winter rapeseed) and 4.5 (silage maize).

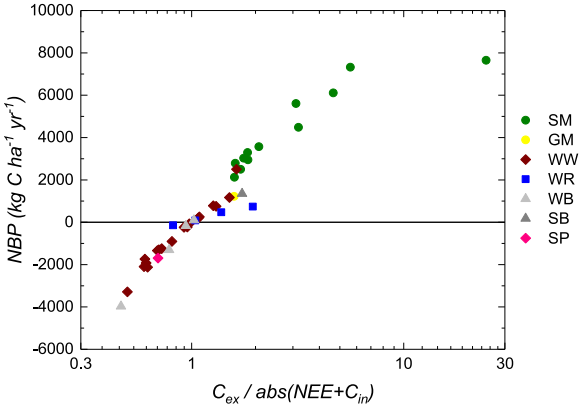

Fig. 9. Carbon export.
Relationship between net biome productivity (NBP) and the ratio of exported carbon to carbon import as the absolute values of net ecosystem exchange (if negative) and organic fertilization. SM: Silage maize, GM: Grain maize, WW: Winter wheat, WR: Winter rapeseed, WB: Winter barley, SB: Summer barley, SP: Spelt. Share computed as percentage of exported carbon in NBP.

4.4. Management strategies to avoid carbon losses

Our findings of net C losses from croplands strongly challenge the '4 per mille goal' as the theoretical annual increase of global SOC stocks needed to compensate for CO_2 emissions from fossil fuels (Minasny et al., 2017). As stated above, the mean annual C loss of 1.19 t C ha^{-1} from our study sites was within the range of values reported in other studies on croplands in Germany or Europe. This significant C source function of croplands is alarming because it promotes global climate change. Another important concern is that diminishing SOC stocks threaten soil quality and thus agricultural production potential (Loveland and Webb, 2003).

Several management recommendations have been forwarded to mitigate C losses from agricultural soils or to enhance soil C sequestration (e.g., Lal, 2004; Smith et al., 2008). In their review, Stockmann et al. (2013) provided a potential C sequestration rate of 0.5–1.0 t C ha^{-1} yr^{-1} for conservation tillage. In non-tilled soils, soil organic matter (SOM) is stabilized due to intensive aggregation and the formation of persistent micro-within-macroaggregate fractions (Six and Paustian, 2014). At our SJ sites, however, the lower tillage intensity did not result in lower net C losses compared to the regularly ploughed KR fields (Tables 2 and 3). The higher C stocks at the SJ sites more likely reflect the clay-rich soils and the cooler climate conditions compared to the KR (Poeplau et al., 2011). By evaluating studies on no-till management and its effects on soil C sequestration and crop productivity, Ogle et al. (2012) identified a threshold of 15% decline in total (above- and belowground) C inputs in no-till versus conventional tillage. Below this threshold, no-till increased SOC stocks due to lower decomposition rates. Eugster et al. (2010) reported that short-term (7 days) respiration rates increased most strongly after late-season inverting moldboard ploughing among several management activities on European croplands. Despite the evidence of positive effects of reduced or no tillage agricultural practices, their potential for C sequestration and climate change mitigation has recently been challenged. This is mainly due to the relatively minor additional C accumulation (Powlson et al., 2014) as well as to the discontinuous application of no-till in practice and potentially elevated nitrous oxide (N_2O) emissions (VandenBygaart, 2015).

Cover crops are often linked to various environmental benefits. Besides positive effects on erosion control and nutrient use efficiencies (Valkama et al., 2015; Komainda et al., 2017), they probably enhance C sequestration because they are generally not removed from the field but incorporated into the soil (Poeplau and Don, 2015). Stockmann et al. (2013) specified a C sequestration potential of 0.2–0.5 t C ha^{-1} yr^{-1} by introducing cover crops in crop rotations. The ability of cover crops to accumulate sufficient biomass before winter, however, strongly depends on species and sowing date (Komainda et al., 2016). Own measurements of cover crop biomass at the end of the growing season indicated very variable plant development ranging from 0.6 (EC5 2015/16) to 5.5 t ha^{-1} (EC3 2017/18) of aboveground DM. As seeding of cover crops generally took place before 1 September to meet the requirements of the EU Common Agricultural Policy, GDD before the end of the vegetation period should have been sufficient for high biomass accumulation (Komainda et al., 2016). Thus, the high variability in cover crop development was most likely controlled by seeded species and growing conditions in late summer and autumn.

On average, cover crop growth strongly reduced C losses after harvest of the main crops from our study sites. In KR, the mean daily fluxes for the period September-October were 13.9 kg CO_2-C ha^{-1} d^{-1} without cover crops (bare soil/stubbles/voluntary emerged weeds or rapeseed) versus 4.8 kg CO_2-C ha^{-1} d^{-1} when cover crops were seeded. The difference was even larger in SJ: 18.7 versus 2.9 kg CO_2-C ha^{-1}

d^{-1}, respectively. Cover crops can only be grown before summer crops. Due to the chosen budgeting for calendar years, C fixation by cover crops in autumn reduces C losses attributed to the previous maincrop. The potentially enhanced soil CO_2 efflux after cover crop incorporation in the following year might therefore increase C losses attributed to the subsequent summer crop. The picture of substantial C losses in silage maize years (Table 3 and Fig. 9), however, would not change essentially by accounting for this effect.

Management related C fluxes were the most important factor affecting the annual NBP of the study sites. As the application of organic fertilizers is known to increase SOC stocks (Tian et al., 2017), historical manure and slurry application on SJ sites might partly explain the higher SOC stocks compared to KR with a traditional rotation of cash crops and low or missing organic fertilizer inputs. Among the SJ sites, EC4 received much lower inputs of organic fertilizers and had the lowest SOC stock in the top soil although only slightly lower compared to EC5. In addition to organic fertilization, residue management represents a main factor for SOC conservation with residue addition generally related to positive effects on C sequestration. Consequently, frequent silage maize cropping (very high C removal) was the main reason for net C losses from the study sites. At EC4, where silage maize was grown only in the last year, the equally high mean NBP was additionally caused by the low net CO_2 uptake of spring barley.

C losses induced by land use changes are expected to attenuate in the long-term until a new equilibrium is reached (Poeplau et al., 2011). As our sites have been utilized as croplands since several decades, one interpretation of the observed C losses is that this might have been initiated by a considerable shift in crop rotations and management (Capriel, 2013). The German Renewable Energy Directive was legislated in 2000 and reimburses power generation from biomass. This led to a great expansion of the area cropped with silage maize for biogas production. According to the farmer managing the KR sites, silage maize has been grown since 2008 due to the installation of a nearby biogas plant. It has replaced grain maize and legumes in crop rotations. In contrast to silage maize, grain maize produces high inputs of aboveground harvest residues. In SJ, silage maize is used for both biogas production and as a forage crop. Therefore, its introduction to crop rotations occurred earlier than in KR. Nonetheless, growing maize for ruminant nutrition is still a rather recent development: due to the larger C stocks in SJ, even there, the time may have been insufficient to reach a new SOC equilibrium.

Maize, as a C4 crop, has a high resource use efficiency in terms of water and N (Wienforth et al., 2018). Our results, however, challenge the expansion of annual bioenergy cropping with the intention of mitigating CO_2 emissions. This strategy needs rejection not only when permanent grassland or natural vegetation is converted to cropland (Don et al., 2012; Abraha et al., 2018), but also when bioenergy maize is grown on historical croplands. In line with our observations, Capriel (2013) reported decreasing SOC contents in top soils of Bavarian croplands (south Germany) during the period 1986–2007. The author attributed these C losses to decreasing amounts of applied farmyard manure and incorporated harvest residues. Higher SOC losses were found on croplands with higher proportions of silage maize, sugar beet and potato in crop rotations. For the northeastern United States, Dell et al. (2018) demonstrated that dairy forage or bioenergy crop rotations that combine silage maize with a multi-year perennial phase of alfalfa are able to sequester SOC. These findings indicate a promising alternative to the conventional rotations with annual crops and raise the need for more research on such kind of land use systems under Central European conditions.

5. Conclusions

Our multi-site approach demonstrated that the inter-annual on-site variability of net ecosystem exchange (NEE) and net biome productivity (NBP) was as large as the inter-site and even inter-region variability. Importantly, we identified the amount of harvested biomass as the major trigger controlling NBP and thus C losses. On the one hand, the high carbon use efficiency of maize compared to C3 crops makes it a valuable crop due to the high amounts of produced shoot biomass. Silage maize cropping with harvest of the whole aboveground biomass, on the other hand, has the potential to decrease soil organic carbon (SOC) stocks and thus deteriorate soil quality. Our results indicate that the recent increase in silage maize cropping for ruminant nutrition and biogas production has disturbed SOC stocks and induced the observed depletion. Particularly in Swabian Jura, high SOC stocks – combined with changing climatic conditions that potentially favor microbial decomposition – indicate that CO_2 emissions from soil C losses might be a long-lasting phenomenon. The recorded mean annual CO_2 emissions in silage maize years (15700 kg CO_2 ha^{-1} yr^{-1}) were substantially higher than what is generally considered as the mitigation potential of bioenergy maize compared to fossil fuels (roughly 10000 kg CO_2-equivalents ha^{-1} yr^{-1}). This makes it highly questionable whether growing silage maize for biogas production is actually a mitigation measure for CO_2 emissions from fossil fuels. The share of silage maize in crop rotations should therefore be low, underlining the need to diversify agroecosystems. Evaluating C sequestration potentials calls for more information on the C budgets of alternative crops such as grain legumes or temporary grass-clover mixtures and on full, more diverse crop rotations.

Declarations of interest

none

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.agee.2019.02.011.

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